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SEP 78 J N DEMARCHI, R K HANING

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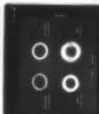
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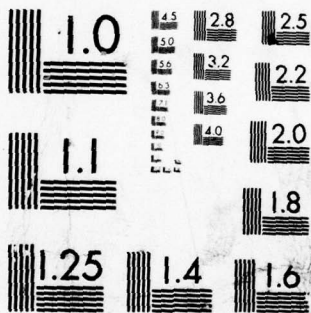
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LIGHTWEIGHT HYDRAULIC SYSTEM EXTENDED ENDURANCE TEST



Rockwell International

Columbus Aircraft Division
4300 East Fifth Avenue
PO Box 1259
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SEPTEMBER 1978

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SUMMARY

One hundred hours of endurance cycling were conducted at 8000 psi and +200°F on hydraulic components in a prior phase of the Lightweight Hydraulic System (LHS) program. The test was completed satisfactorily with no significant failures. Further evaluation was required to estimate the potential endurance life of the test hardware. Endurance cycling was therefore extended for 100 additional hours; the results are presented in this report. The components tested were:

- | | |
|-------------------------------|--------------------------------------|
| 1. Variable displacement pump | 6. Seals: dynamic (8)
static (14) |
| 2. Relief valve | 7. Hydraulic fluid (MIL-H-83282) |
| 3. Restrictors (2) | 8. Tubing (3 sizes) |
| 4. Solenoid valves (2) | 9. Fittings |
| 5. Flow control valve | 10. Hoses (2) |

Component performance was measured before resumption of endurance cycling and at 150 and 200 hours. Testing was completed with no major problems. Significant observations made were as follows:

- Standard O-rings and TFE backups can be used in static seal applications (diametral, face, boss)
- Off-the-shelf seals are satisfactory for dynamic applications (piston, rod)
- Estimated potential life of the pump was 1000+ hours
- Restrictor and flow control valve performance was estimated to be satisfactory for the life of the aircraft

PREFACE

This report documents research conducted by the Columbus Aircraft Division of Rockwell International Corporation, Columbus, Ohio, under Contract N62269-78-C-0005 with the Naval Air Development Center, Warminster, Pennsylvania. Technical direction was administered by Mr. J. Ohlson, Program Engineer, Fluid Systems Section, Aircraft and Crew Systems Technology Directorate, Naval Air Development Center (6061), and Mr. N. Webb, Head, Fluid Systems Section, Mechanical Equipment Branch, Naval Air Systems Command (AIR-53031).

This report presents the results of an extended endurance test conducted on aircraft-type hardware designed for use in an 8000 psi hydraulic system. This work is related to tasks performed under Contracts NOW-65-0567-d, N00019-68-C-0352, N00156-70-C-1152, N62269-71-C-0147, N62269-72-C-0381, N62269-73-C-0700, and N62269-74-C-0511.

Appreciation is extended to the many individuals who provided helpful support and constructive criticism of the program; in particular, Mr. N. Webb of the Naval Air Systems Command, and Mr. J. Ohlson and Mr. J. Dever of the Naval Air Development Center.

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1.0 INTRODUCTION

1.1 BACKGROUND INFORMATION

The development of a lightweight hydraulic system (LHS) for military aircraft has been a joint undertaking by the Navy and Rockwell International since 1966. The LHS concept involves the use of an 8000 psi pressure level to minimize the weight and space requirements of hydraulic components and lessen the severity of the weight and space restrictions present in high density, supersonic aircraft.

Prior phases of the program have examined many aspects of very high pressure hydraulic systems as applied to aircraft. The first phase was a theoretical study of pressure levels up to 20,000 psi, and concluded that operating pressures up to 9000 psi are feasible, Reference 1. The second phase consisted of: (1) a math model computer simulation to establish the dynamic response of two schematically simple hydraulic systems operating with pressures up to 12,000 psi; and (2) laboratory tests to confirm trends noted at lower pressures and gain operating experience with pressure levels up to 9000 psi, Reference 2. Phase III verified the math model dynamic response at 6000 and 9000 psi by means of laboratory tests conducted on a mass-loaded servo actuator powered by a very high pressure aircraft-type pump, Reference 3. The pump was designed and built by Abex Corporation in Oxnard, California, under the technical guidance of the Columbus Aircraft Division (CAD). The 9000 psi servo actuator was designed and fabricated by CAD and sized to simulate the RA-5C horizontal stabilizer flight control "muscle" actuator.

Phase IV involved hardware performance tests, selection of 8000 psi as the LHS operating pressure level, development of LHS design criteria, and use of these criteria in a study made to determine space and weight savings achieved if an 8000 psi hydraulic system were applied to the F-14 airplane, Reference 4. Phase V was an investigation of the detail performance characteristics of 8000 psi hardware including a variable delivery pump, three port solenoid valve, power servo actuator, and notched spool/sleeve type flow control valve -- all operating with MIL-H-83282 fluid, Reference 5. In addition, the computer simulation of Reference 3 was updated and compared to hardware performance, and an industry-wide survey was made to locate 8000 psi static and dynamic seals. Phase VI consisted of preparations for conducting an endurance test on aircraft-type hardware designed for use in an 8000 psi hydraulic system, Reference 6.

Phase VII was a 100 hour endurance test conducted at 8000 psi and +200°F on lightweight hardware in a laboratory hydraulic system designed to be representative of aircraft-type circuitry. The hardware cycled were: pump, relief valve, restrictors, solenoid valves, flow control valve, seals (22), hydraulic fluid (MIL-H-83282), tubing, fittings, and hoses. The test was completed with no major problems. This phase also included the design and fabrication of an 8000 psi aileron actuator for the T-2C airplane, Reference 7.

Phase VIII involved preparations for flight testing an 8000 psi hydraulic system. The major tasks were test installation design, heat rejection analysis, and laboratory compatibility tests of system components, Reference 8. An 8000 psi lateral control system was installed on a T-2C airplane in Phase IX, Reference 9. Four pilots evaluated the test installation, accumulating 11.5 flight hours. The 8000 psi system functioned exceptionally well.

The LHS Exploratory Development Program has shown that state-of-the-art advances are not required to operate at 8000 psi, and that significant advantages can be gained by using 8000 psi instead of the conventional 3000 psi pressure level.

1.2 OBJECTIVE

The objective of Phase X of the LHS Exploratory Development Program was to extend the 100 hour endurance test conducted in Phase VII to 200 hours.

1.3 TECHNICAL APPROACH

The 8000 psi hydraulic system evaluated in Phase VII satisfactorily completed 100 hours of laboratory endurance cycling. No major failures occurred, however a fatigue crack developed in the pump barrel after 66 hours of cycling. A second pump was used to complete the test. All hardware in the system was in excellent condition at 100 hours (including the second pump). Further testing was required to estimate endurance potentials and assure that changes to be made in the pump were satisfactory.

Technical consulting services were provided by the Columbus Aircraft Division to support NADC in procuring a modified 8000 psi pump. The modification was accomplished by the Aerospace Division of Abex Corporation in Oxnard, California.

The modified pump was installed in the existing 8000 psi hydraulic test system at CAD. The pump and system components were then subjected to 100 additional hours of endurance cycling. Test conditions were identical to those used in Reference 7. Fluid temperatures ranged from +200 to +260°F; fluid flow was varied by automatic cycling of solenoid valves, servo actuators, and seal test fixtures. Hardware performance was measured before resumption of endurance cycling, and after completion of 150 and 200 hours of testing. After final leakage checks were made, the seal test fixture was disassembled to inspect individual seals for wear and incipient failures.

2.0 RESULTS

2.1 SYSTEM

The test system, shown on Figure 1, is described in detail in Reference 7. Components in the system subjected to endurance cycling were:

<u>Description</u>	<u>Manufacturer</u>
* Variable displacement pump	Aerospace Division of Abex Corporation
* Hydraulic relief valve	Teledyne Republic
Hydraulic restrictors (2 ea.)	The Lee Company
3-Port solenoid valves (2 ea.)	Sterer Engineering and Manufacturing Co.
Flow control valve	Rockwell International (design only) Aircraft Nitriding Co.
Seals: Dynamic (8 ea.) Static (14 ea.)	Bal-Seal Engineering Co. Cook-Airtomic Division of Dover Corporation Greene, Tweed & Co. Parker Seal Co. Pressure Science, Inc. Rockwell International (design only) W. S. Shamban and Co. United Aircraft Products, Inc.
Hydraulic Fluid (MIL-H-83282)	Mobil Oil Corporation
21-6-9 CRES tubing	Trent Tube Division of Colt Industries
Fittings (Dynatube)	Resistoflex Corporation
Hoses (2 ea.)	Titeflex Division of Atlas Corporation Resistoflex Corporation

Items marked with an asterisk (*) differed from those tested in the first 100 hours of cycling, Reference 7. The pump was modified; this is discussed in Section 2.2. The relief valve was a different unit since the original valve (manufactured by Pneudraulics) was in a test installation on a T-2C airplane, Reference 11.

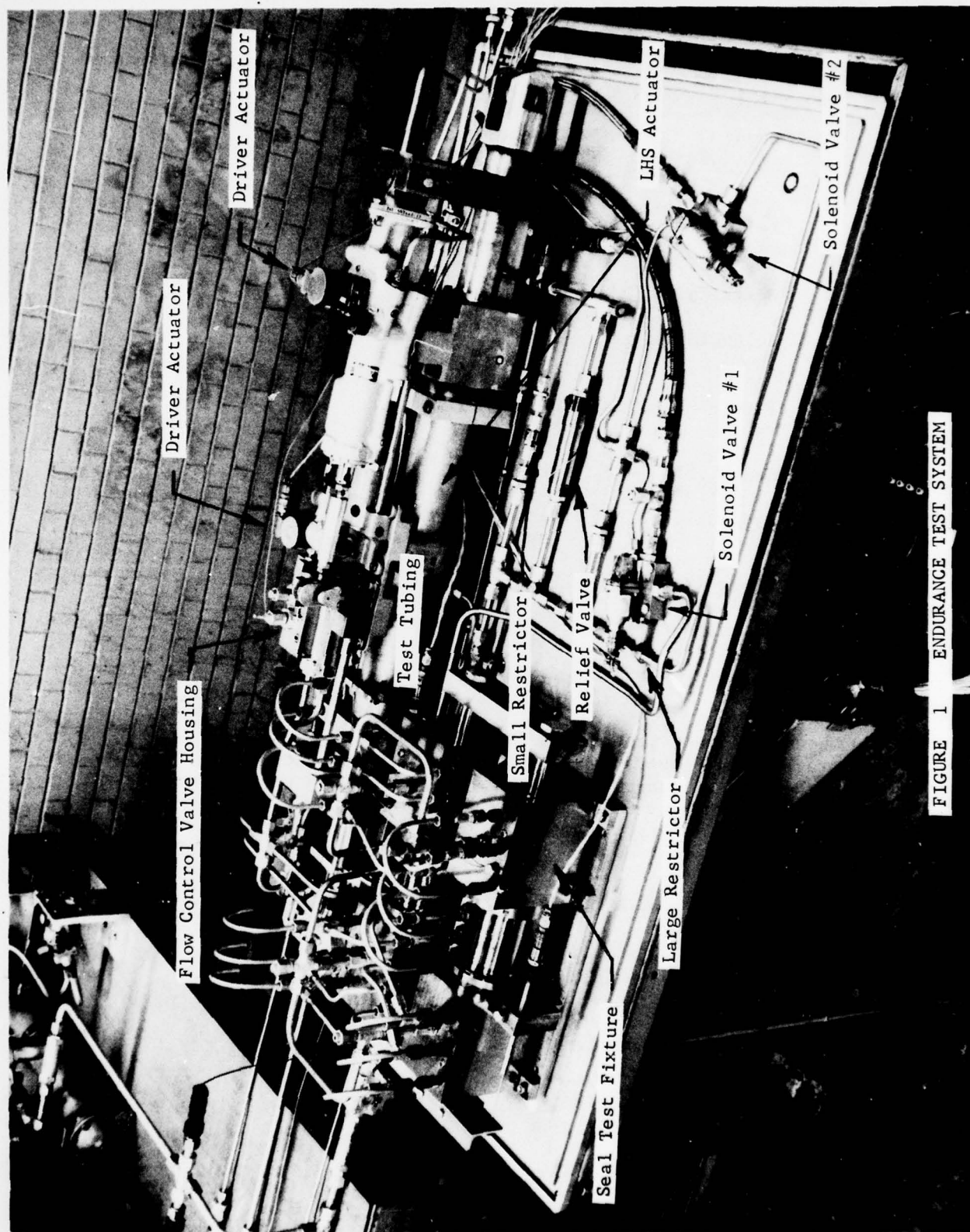


FIGURE 1 ENDURANCE TEST SYSTEM

Component performance was measured at 100, 150, and 200 hours. Performance checks made were:

Pump	Discharge flow Heat rejection Case drain filter debris
Relief Valve	Internal leakage Cracking pressure
Restrictors (2)	Flow
Solenoid Valves (2)	Internal leakage
Flow control valve	Null leakage Flow gain
Seals (22)	Leakage
Hydraulic Fluid	Viscosity Contamination
Hoses (2)	External leakage
Fittings (12)	External leakage
Tubing	External leakage

The 100 hour endurance test was conducted over a period of 20 days; run time averaged 4 to 6 hours per day. The test temperature was $+200 \pm 10^{\circ}\text{F}$ fluid at the pump discharge port. Pump speed was 4000 rpm. Temperature stabilization was achieved by means of a controller and an oil-to-water heat exchanger. A summary of average temperatures maintained during cycling is given below:

<u>Thermocouple Location</u>	<u>Temperature, $^{\circ}\text{F}$</u>
Pump inlet fluid	+186
Pump discharge fluid	+203
Pump case drain fluid	+254
System return fluid	+225
Spool/sleeve housing (on LHS actuator)	+210
Seal test fixture (cartridge housing)	+202
Enclosure air	+151

A performance summary covering 200 hours of endurance cycling is given on Table I; data for 0 and 50 hours were taken from Reference 7. Results of the final 100 hours of testing are given in the following sections. Component descriptions and test procedure details are discussed in Reference 7.

2.2 PUMP

The test pump was designed and fabricated by the Aerospace Division of Abex Corporation in Oxnard, California. The unit, identified as M/N AP6V-57, P/N 63022, is a pressure compensated, variable displacement, axial piston pump. Rated output at 4000 rpm and +240°F inlet fluid temperature is 14 gpm at 7850 psi; full displacement is 0.95 CIPR. Displacement was reduced approximately 50% to limit input horsepower requirements. This was done by inserting a spacer in the stroking piston bore.

The rotating barrel in the original LHS pumps, S/N 109421 and S/N 109422, was made of Mueller bronze 603. The maximum working stress level was approximately 13,000 psi, and fatigue strength was 30,000 psi. The barrel cracked in S/N 109421 after 65.8 hours of cycling in the endurance test reported by Reference 7; the remaining 34.2 hours of cycling were completed using S/N 109422. At this point the total operating time on S/N 109421 was 85.8 hours, and on S/N 109422 was 206.2 hours, Reference 7.

Both LHS pumps were shipped to the Aerospace Division of Abex Corporation for modification. The rotating barrel in each pump was changed to 4130 steel with an ultimate strength of 125,000 psi. The working stress level was estimated to be 24,000 psi. Sleeves made from Mueller brass 605 were swaged in the piston bores; sleeve wall thickness was 0.0625 inches. The barrel face was plated with shoe bronze (95% Cu - 5% Sn). No other parts in the pumps were modified. Pump S/N 109422 was used for the tests reported herein.

It should be noted that prior to modifying the AP6V-57 pumps, Abex fabricated an 8000 psi, 3 gpm pump with a steel barrel and Mueller bronze sleeves. This unit, designated as M/N AP1V-106, was used for the LHS and AFCAS flight test programs, References 9 and 11, and currently has 113 hours of satisfactory operation.

TABLE I PERFORMANCE SUMMARY

COMPONENT TEST PARAMETER	* 0 HRS	* 50 HRS	100 HRS	150 HRS	200 HRS
<u>PUMP</u>					
DISCHARGE FLOW @ 7500 PSI, GPM	5.97	5.19	6.52	6.50	5.45
HEAT REJECTION @ 8000 PSI, BTU/MIN	574	722	592	571	549
			→ MODIFIED PUMP		
<u>RELIEF VALVE</u>					
INTERNAL LEAKAGE, DPM	0	0	9	NM	2
CRACKING PRESSURE, PSI	8550	8500	8600	NM	8600
			→ TELEDYNE REPUBLIC VALVE		
<u>RESTRICTORS (2)</u>					
FLOW, GPM					
LARGE RESTRICTOR	1.98	2.03	1.95	1.96	1.96
SMALL RESTRICTOR	.36	.37	.44	.44	.45
<u>SEALS (22)</u>					
	SEE TABLE V				
<u>SOLENOID VALVES (2)</u>					
INTERNAL LEAKAGE (VALVE 'OFF')					
VALVE S/N 1, DPM	4	7	9	17	24
VALVE S/N 2, DPM	7	4	4	10	22
<u>FLOW CONTROL VALVE</u>					
NULL LEAKAGE, CC/MIN	125	125	142	140	137
FLOW @ +.077 IN. SPOOL TRAVEL, GPM	3.52	3.44	3.64	3.45	3.45
<u>HYDRAULIC FLUID (MIL-H-83282)</u>					
VISCOSITY, CS	17.5	17.7	17.7/16.8	NM	16.9
CONTAMINATION, COUNTS					
5-15μ RANGE	NM	NM	95,145	39,318	3637
15-25μ RANGE	6665	11,985	462	315	57
25-50μ RANGE	0	10	139	18	10
	→ BATCH #186 (7.3 GAL)		→ 1 GAL OF BATCH #171 ADDED		
	→ ALL 25μ FILTER ELEMENTS		→ 5μ ELEMENT PUT IN CASE DRAIN FILTER		
<u>HOSES (2)</u>					
EXTERNAL LEAKAGE, DPM					
-4 SIZE	0	0	0	0	0
-6 SIZE	0	0	0	0	0
<u>FITTINGS (12)</u>					
EXTERNAL LEAKAGE, DPM	0	0	0	0	0
<u>TUBING (21-6-9 CRES)</u>					
EXTERNAL LEAKAGE, DPM	0	0	0	0	0

* DATA FROM REFERENCE 7
 DPM = DROPS PER MINUTE
 NM = NOT MEASURED

Test Procedure

Pump performance was based on the following operating conditions and test parameters:

Compensator setting	8000 psig
Pump speed	4000 rpm
Pump displacement	0.45 CIPR (approx.)
Inlet pressure	30 psig
Fluid temperatures	Inlet °F (recorded) Discharge, +200°F Case Drain, °F (recorded)
Input torque	1b-in (recorded)
Flow	Discharge, gpm (recorded) Case drain, gpm (recorded)
Discharge pressure	4000 to 8000 psig
Case pressure	45 to 70 psig

Test Results

Performance of the modified pump is summarized below:

<u>Endurance Test Check Point</u>	<u>Discharge Pressure, psig</u>	<u>Discharge Flow, gpm</u>	<u>Case Flow, gpm</u>	<u>Heat Rejection, BTU/min</u>
100 Hours	7500	6.52	1.42	500
	8000	0	2.14	592
150 Hours	7500	6.50	1.42	477
	8000	0	2.24	571
200 Hours	7500	6.45	1.57	467
	8000	0	2.25	549

Overall efficiency is approximately 91% when the pump is operated at its full rated capacity of 14 gpm, Reference 5. Lowering maximum discharge flow to 6.5 gpm reduced efficiency to 72%. This was due to operating tare of the pump which was present regardless of the displacement setting. Heat rejection decreased 7% during the 100 hour test, indicating performance improved as the pump "wore in".

A normal quantity of wear particles was observed in the case drain filter during the 100, 150, and 200 hour checks. Pump wear was therefore considered to be satisfactory.

Total operating time on LHS pump S/N 109422 is currently 306 hours; time on the rotating steel barrel is 100 hours. Internal parts of the pump were examined prior to the extended endurance test; all parts subject to wear were observed to be in excellent condition. Based on the test data, pump life was estimated to be more than 1000 hours.

2.3 RELIEF VALVE

Relief valve, P/N 1108A, fabricated by PneuDraulics, Inc., was evaluated during the first 100 hours of endurance cycling, Reference 7. This valve was also used in the 8000 psi hydraulic system for the LHS and AFCAS flight test programs, References 9 and 11, and is currently installed in a T-2C airplane for a follow-on AFCAS flight test program. Valve P/N 1108A was therefore not available for the LHS extended endurance test reported herein. A prototype relief valve, P/N 2-2177-4, supplied by Teledyne Republic Manufacturing, Cleveland, Ohio, was used for the extended endurance test. This unit was similar to the PneuDraulics valve in both size and design.

Performance of valve P/N 2-2177-4 is summarized below:

<u>Endurance Hours Completed</u>	<u>Cracking Pressure, psig</u>	<u>Internal Leakage at 8000 psi, dpm</u>
0	8600 (est.)	9
100	8600 (est.)	2

The valve did not have sharply defined cracking and re-seating characteristics. The above cracking pressures were estimates based on 0.2 gpm flow through the unit. With 9200 psig applied (the highest possible compensator setting on the LHS pump), maximum flow through the valve was only 1 gpm. This could easily be increased by a redesign. Internal leakage across the poppet was not affected by the 100 hour test; no external leakage was observed.

2.4 RESTRICTORS

Flow restrictors evaluated in the extended endurance test were P/N VDLX0484000A (small restrictor) and P/N JEFX0483000A (large restrictor) manufactured by The Lee Company. Flow through the restrictors with 8000 psig applied and +110°F MIL-H-83282 fluid is summarized below:

<u>Small Restrictor</u>		<u>Large Restrictor</u>	
<u>Endurance Hours Completed</u>	<u>Flow, gpm</u>	<u>Endurance Hours Completed</u>	<u>Flow, gpm</u>
0	0.36	0	1.98
50	0.37	16.7	2.03
100	0.44	33.3	1.95
150	0.44	50	1.96
200	0.45	66.7	1.96

Flow changes caused by endurance cycling were considered acceptable; the performance of both restrictors was therefore satisfactory. Projected life of the restrictors was estimated more than the life of the airframe.

2.5 SOLENOID VALVES

The solenoid valves, built by Sterer Engineering and Manufacturing Company, were identified as P/N 15390-1, S/N 001 and S/N 002. Internal leakage measurements were taken with the cylinder port capped, return port open, and 8000 psi applied to the pressure port. Leakage rates were as follows:

<u>Endurance Test Hours Completed</u>	<u>Number of Cycles Completed</u>	<u>Internal Leakage, drops/min</u>			
		<u>Valve S/N 001</u>		<u>Valve S/N 002</u>	
		<u>Off</u>	<u>On</u>	<u>Off</u>	<u>On</u>
0	0	4	2	7	4
50	200	7	26	4	11
100	400	9	13	4	12
150	600	17	19	10	16
200	800	24	31	22	40

Each valve was subjected to a total of 1,760,000 pressure pulsations around the 8000 psi pressure level. Although the internal leakage of both valves was beginning to increase at the conclusion of testing, valve performance was satisfactory throughout the test. Valve S/N 002 had external leakage at the rate of 5 drops/minute when the unit was energized electrically. The leak emanated from a titanium gasket seal.

2.6 FLOW CONTROL VALVE

Spool/sleeve P/N 4212-03-11 was designed by the Columbus Aircraft Division and fabricated by Aircraft Nitriding Company. Valve endurance performance was based on null leakage and flow gain. Values of these parameters versus test time are shown below:

<u>Endurance Test Hours Completed</u>	<u>Number of Spool Oscillations</u>	<u>Null Leakage, cc/min</u>	<u>Flow @ +0.077 in. Spool Displ., gpm</u>
0	0	125	3.52
50	220,000	125	3.44
100	440,000	142	3.54
150	660,000	140	3.45
200	880,000	137	3.45

The above data indicate that no significant change in valve performance occurred. Erosion on the spool spindle after 880,000 oscillations was minor and had no effect on valve performance, Figure 2. Based on the test data and a visual examination for wear, the potential life of the valve was estimated to be more than the life of the airframe.

2.7 SEALS

Eighteen different seals were evaluated concurrently in a seal test fixture, P/N 4252-03, designed by the Columbus Aircraft Division and built by Lancaster Metal Products, Figure 3. Seal types and number () tested were: piston (2), rod (4), diametral (4), face (4), and boss (4). Four additional seals were evaluated in LHS actuator P/N 4212-01, designed and fabricated by CAD, Reference 3. Seals tested were: piston (1), rod (1), diametral (1), and boss (1). Details of the seals, including materials, anti-extrusion devices, surface finish, extrusion gap, etc., are given on Table II.

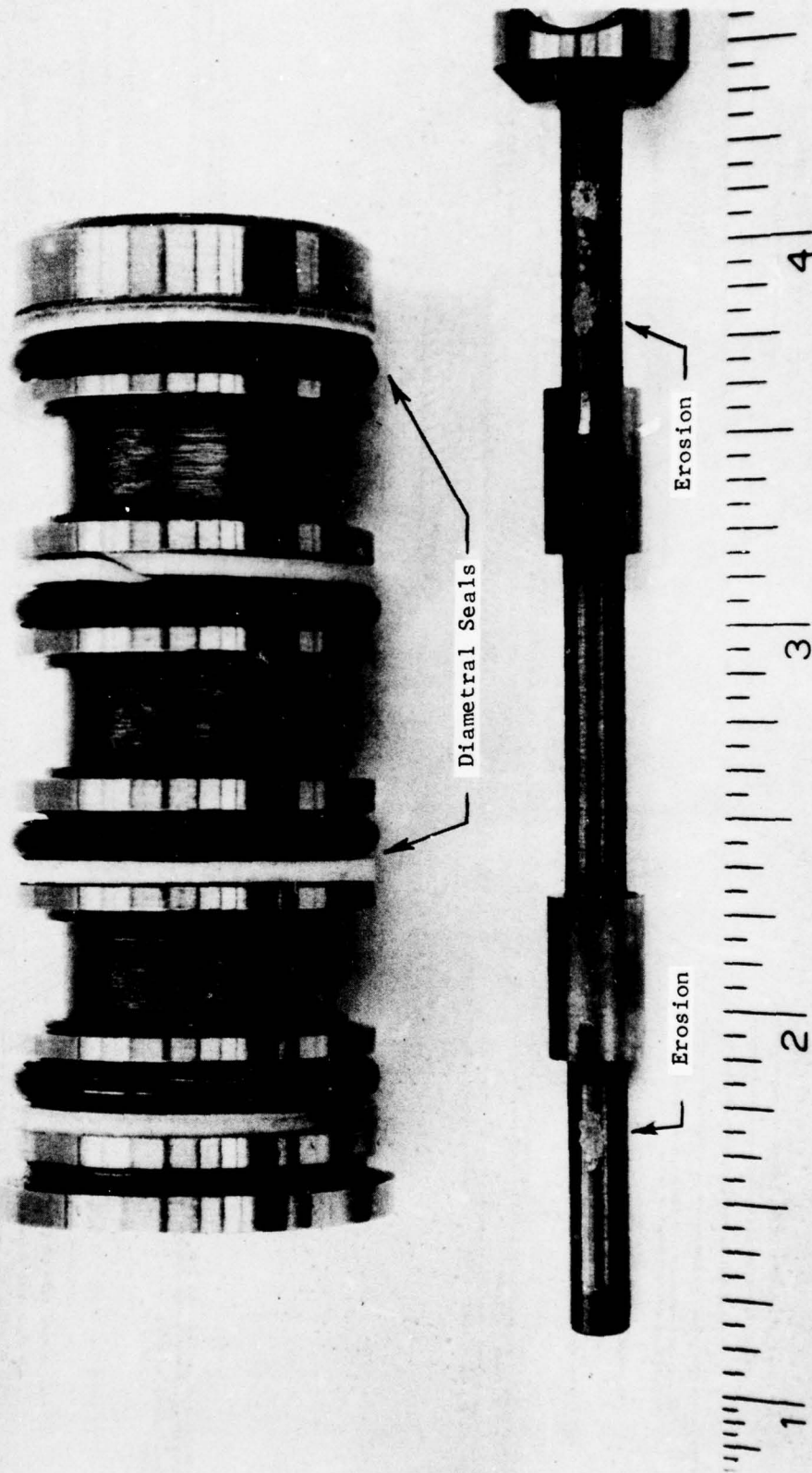


FIGURE 2 FLOW CONTROL VALVE AFTER ENDURANCE TEST

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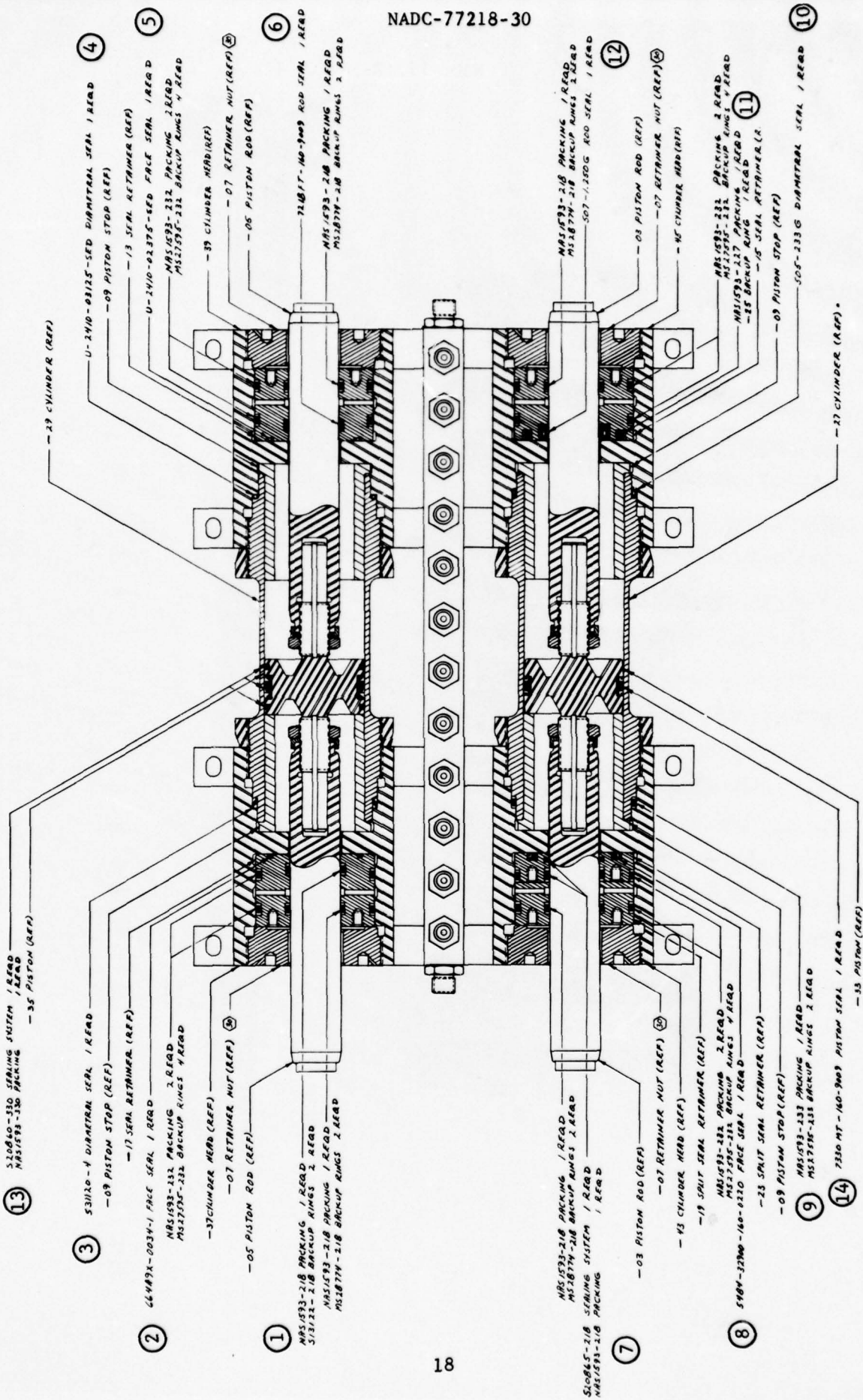


FIGURE 3 SEAL LOCATIONS IN TEST FIXTURE

TABLE II TEST SEAL CONFIGURATIONS

SEAL TYPE	LOCATION	PART NO.	DESIGNER/ SUPPLIER	SEALING ELEMENTS		ANTI-EXTRUSION DEVICES		SEALING SURFACE FINISH	EXTRUSION GAP, IN.	SEAL CAVITY DESIGN
				TYPE	MATERIAL	TYPE	MATERIAL			
PISTON	A	IESDA-2040	COOK AIRTOMIC	SPLIT RING (S)	VVO C	NONE	NONE	8-16	.0017	NON-STD.
	14	7330MT-160-9009	GREENE, TWEED	T' SECTION RING	NITRILE	1. SPLIT RING (R) 2. SPLIT RING (R)	1. MOLY LOADED, GLASS FILLED TFE 2. 316 CRES	8-16	.0022	STD. WITH REDUCED GAP
	13	920860-350	SHAMBAN	1. CHANNEL SECTION 2. O-RING	1. GLASS & MOLY REINFORCED TFE 2. FLUOROCARBON	1. SPLIT RING (R) 2. SURGE BUFFER (SPLIT RING)	1. POLYESTER 2. POLYESTER	4-8	.0022	NON-STD.
ROD	A	SP-4246 4-16E	COOK AIRTOMIC	SPLIT RING (R)	VVO C	NONE	NONE	8-16	.0050	NON-STD.
	12	507-12505	BAL-SEAL	C' SECTION RING, SPRING LOADED	GRAPHITE FILLED TFE	NONE	NONE	4-8	.0015	NON-STD. SPLIT GROOVE REED.
	6	7218FT-160-9009	GREENE, TWEED	T' SECTION RING	NITRILE	1. SPLIT RING (R) 2. SPLIT RING (R)	1. MOLY LOADED, GLASS FILLED TFE 2. 316 CRES	8-16	.0015	STD. WITH REDUCED GAP
	1	513122-218-W NAS 1593-218	ROCKWELL/SHAMBAN	O-RING	FLUOROCARBON	SPLIT RING (R)	15% GLASS, 8% MOLY REINFORCED TFE	8-16	.0015	MOD. STD.
	7	520946-218 NAS 1593-218	SHAMBAN	1. CHANNEL SECTION 2. O-RING	1. GLASS & MOLY REINFORCED TFE 2. FLUOROCARBON	1. SPLIT RING (R) 2. SURGE BUFFER (S)	1. POLYESTER 2. POLYESTER	4-8	.0015	MOD. STD. SPLIT GROOVE REED.
DIAMETRAL	10	505-2336	BAL-SEAL	C' SECTION RING, SPRING LOADED	GRAPHITE FILLED TFE	NONE	NONE	32	.0010	NON-STD.
	9	NAS 1593-235 MS 27595-235	ROCKWELL	O-RING	FLUOROCARBON	CONTINUOUS RING (R)	TFE	32	.0010	MOD. STD.
	3	53120-4	SHAMBAN	B' SECTION RING	TFE	CONTINUOUS RING (R)	BRASS	32	.0010	NON-STD.
	4	U-2410-03125-5ED	UNITED AIRCRAFT	O-RING (SELF-ENERGIZED)	321 CRES TFE COATED	NONE	NONE	32	.0010	NON-STD.
	A	NAS 1593-116 MS 28774-116	ROCKWELL	O-RING	FLUOROCARBON	SPIRAL RING (R)	TFE	32	.0015	MOD. STD.
FACE	8	5484-32900-160-0020	GREENE, TWEED	L' SECTION RING	NITRILE	CONTINUOUS RING (I)	MOLY LOADED, GLASS FILLED TFE	63	-	-
	2	649491-0034-1	PRESSURE SCIENCE	B' SECTION RING	INCO A-750, SILVER PLATED	NONE	NONE	63	-	-
	11	4782-03-26 NAS 1593-227	ROCKWELL	O-RING	FLUOROCARBON	CONTINUOUS RING (I)	TFE	63	-	-
	5	U-2410-02378-5ED	UNITED AIRCRAFT	O-RING (SELF-ENERGIZED)	321 CRES TFE COATED	NONE	NONE	63	-	-
BOSS	17	NAS 1596-06	ROCKWELL	O-RING	FLUOROCARBON	NONE	NONE	32	-	STD.
	A	53121-6	SHAMBAN	B' SECTION RING	TFE	CONTINUOUS RING (R)	BRASS	32	-	NON-STD.
	15	U-700415-065	UNITED AIRCRAFT	O-RING (SELF-ENERGIZED)	304 CRES SILVER PLATED	NONE	NONE	32	-	STD.
	16	U-700415-06E	UNITED AIRCRAFT	O-RING (SELF-ENERGIZED)	304 CRES TFE COATED	NONE	NONE	32	-	STD.
	18	NAS 1593-012 (R F 4408-13)	ROSAN/PARKER	O-RING	FLUOROCARBON	NONE	NONE	32	-	NON-STD.

ABBREVIATIONS

TFE TETRAFLUOROETHYLENE
STD. STANDARD
MOD. MODIFIED

Static leakage measurements were taken at room temperature with 100 psi, then 8000 psi applied across the seals. Leakage was measured after waiting 3 minutes for the rate to stabilize, and was checked at 100, 150, and 200 hours. The dynamic seals were subjected to a total of 880,000 piston oscillations at the conclusion of testing; the static seals were exposed to a total of 1,760,000 pressure oscillations. Test seal leakage at 0, 50, 100, 150, and 200 hours is listed on Table III. Results of visual inspections conducted after the completion of testing are given on Table IV.

A summary of conclusions made after analyzing the test data is presented on Table V. The number of satisfactory seals is given below:

<u>Seal Type</u>	<u>Number of Satisfactory Seals</u>	<u>Number of Unsatisfactory Seals</u>
Piston	1	2
Rod	3 (+1 undecided)	1
Diametral	4	1
Face	3	1
Boss	<u>3</u>	<u>2</u>
	14 (+1 undecided)	7

2.8 FLUID

A synthetic hydrocarbon base hydraulic fluid conforming to MIL-H-83282 was evaluated in the test system. System capacity was 7.3 gallons. During checkout tests prior to beginning the second 100 hours of endurance cycling, approximately 1 gallon of new MIL-H-83282 was added to restore the reservoir fluid level. The new fluid was from batch #171; the original fluid was from batch #186. (Both batches were manufactured by the Mobil Oil Company.)

Four external leaks occurred during the extended endurance test: 2 boss seals and 1 diametral seal leaked on the seal test fixture, and a static seal leaked on solenoid valve #2. This fluid was collected daily and returned to the reservoir. Component performance checks conducted at 100 and 150 hours required minor plumbing changes. Fluid released during these changes was collected and returned to the system. All replaced fluid was run through a 5 μ filter before entering the reservoir.

TABLE III SEAL LEAKAGE SUMMARY

SEAL TYPE	LOCATION	PART NO.	DESIGNER/ SUPPLIER	LEAKAGE											
				DATA FROM REFERENCE 7								EXTENDED ENDURANCE TEST			
				0 HOURS	50 HOURS	100 HOURS	100 HOURS	150 HOURS	200 HOURS	0 HOURS	50 HOURS	100 HOURS	150 HOURS	200 HOURS	200 HOURS
				100 PSI	8000 PSI	100 PSI	8000 PSI	100 PSI	8000 PSI	100 PSI	8000 PSI	100 PSI	8000 PSI	100 PSI	8000 PSI
PISTON	A	123DX-2040	COOK AIRTOMIC	6.9 CC/M	2.9 CC/M	15.5 CC/M	12 D/M	26.4 CC/M	59 D/M	14 D/M	14 D/M	14 D/M	16 D/M	60 CC/M	5.5 CC/M
"	14	7330MT-160-9009	GREENE, TWEED	T*	1 D/2M	T	T*	0	T	2 D/M	0	3 D/M	2 D/M	2 D/M	T*
"	* 13	S20860-330 NAS 1593-330	SHAMBAN	1 D/M	T*	T	T	32 CC/M	14 D/M	94 D/M	T	50 CC/M	2 CC/M	27 CC/M	T
ROD	A	SP-4246-4-162	COOK AIRTOMIC	3 D/M	6 D/M	T*	2 D/M	2 D/M	3 D/M	3 D/M	4 D/M	9 D/M	7 D/M	4 D/M	5 D/M
"	12	507-1.2506	BAL-SEAL	0	0	0	0	T	T	0	0	T	T	T	T
"	6	7218FT-160-9009	GREENE, TWEED	0	0	0	0	T*	1 D/2M	0	0	89 D/M	96 D/M	1 D/M	T*
"	1	513122-218 NAS 1593-218	ROCKWELL/ SHAMBAN	T	0	2 D/M	0	T	1 D/M	T	1 D/2M	6 D/M	5 D/2M	38 D/M	20 D/M
"	7	S20865-218 NAS 1593-218	SHAMBAN	0	0	0	0	0	T	0	0	T*	0	1 D/3M	0
DIAMETRAL	10	505-2336	BAL-SEAL	T*	T	0	0	0	0	0	0	T	0	0	T
"	9	NAS 1593-233 MS 27595-233	ROCKWELL	T	0	0	0	T	2 D/M	0	0	0	0	0	0
"	3	531120-4	SHAMBAN	0	0	0	0	0	0	0	T	T	T*	T	T*
"	4	U-2410-03125-SED	UNITED AIRCRAFT	T	T	1 D/M	11.1 CC/M	7.2 CC/M	230 CC/M	14 CC/M	580 CC/M	47 CC/M	38 CC/M	19 CC/M	876 CC/M
"	A	NAS 1593-116 MS 28774-116	ROCKWELL	LEAKAGE NOT MEASURED **											
FACE	8	5484-32900-160-0220	GREENE, TWEED	T	0	0	0	T	T	0	T	T	T*	T*	1 D/6M
"	2	664A9X-0034-1	PRESSURE SCIENCE	T	T	0	0	T	T	0	T*	1 D/3M	1 D/M	4 D/M	4 D/M
"	11	4252-03-25 NAS 1593-227	ROCKWELL	T	0	0	0	T	T	0	T	T*	T*	T*	T
"	5	U-2410-02375-SED	UNITED AIRCRAFT	T	0	0	0	T	1 D/2M	0	T	0	T	T*	T*
BOSS	17	NAS 1596-06	ROCKWELL	0	0	0	0	0	0	0	0	0	0	0	0
"	A	531121-6	SHAMBAN	0	0	0	0	0	0	0	0	0	0	0	0
"	15	U-700413-062	UNITED AIRCRAFT	0	0	0	T	0	T*	0	T	0	2 D/HR	0	3 D/HR
"	16	U-700413-063	UNITED AIRCRAFT	0	0	0	T*	0	1 D/5M	0	T	0	4 D/HR	0	6 D/HR
"	18	NAS 1593-012 (RF 9906-13)	ROSAN/PARKER	0	0	0	0	0	0	0	0	0	0	0	0

ABBREVIATIONS

A LHS ACTUATOR
 CC CUBIC CENTIMETER
 D DROP (FLUID)
 1,2, ETC. SEAL LOCATION; SEE FIG. 3
 M MINUTE (TIME)
 S SATISFACTORY
 T TRACE
 T* LESS THAN ONE DROP
 U UNSATISFACTORY
 HR HOUR

* PRESSURE APPLIED TO -37 CYLINDER HEAD
 LEAKAGE MEASURED AT -39 CYLINDER HEAD

** SEAL CONDITION SATISFACTORY AT 200 HOURS

TABLE IV VISUAL INSPECTION SUMMARY

SEAL TYPE	LOCATION	PART NO.	DESIGNER/ SUPPLIER	COMMENTS	SEE FIGURE NO.
PISTON	14	73J0MT-160-9009	GREENE, TWEED	<ol style="list-style-type: none"> 1. TEE SEAL IN EXCELLENT CONDITION; NO EVIDENCE OF NIBBLING OR EROSION 2. TFE BACKUPS IN EXCELLENT CONDITION 3. CYLINDER BORE HAD NO SIGNIFICANT WEAR OR SCORING, JUST POLISHING 	4
PISTON	13	S20860-330 NAS 1593-330	SHAMBAN	<ol style="list-style-type: none"> 1. O-RING SEVERELY CHEWED 2. POLYESTER BACKUP NEXT TO CAP (ON -39 SIDE) BROKEN IN SEVERAL PIECES. ALL OTHER BACKUPS IN EXCELLENT CONDITION 3. CAP SEAL WEARING SURFACE IN EXCELLENT CONDITION 4. CYLINDER BORE HAD NO SIGNIFICANT WEAR OR SCORING, JUST POLISHING 5. BUFFER RINGS IN EXCELLENT CONDITION 6. SIGNIFICANT NUMBER OF LARGE BeCu PARTICLES FOUND INSIDE CYLINDER CHAMBER. BeCu PISTON STOP DID NOT CONTACT -39 CYLINDER HEAD AS DESIGNED. INSTEAD, O.D. EDGE OF STOP CONTACTED AN EDGE INSIDE CYLINDER HEAD. FULL LOAD OF PISTON TAKEN BY THE TWO EDGES. O.D. EDGE ON PISTON STOP WAS THEREFORE FRAGMENTED DUE TO INSUFFICIENT BEARING AREA. 7. TOTAL EFFECT OF BeCu PARTICLES ON PISTON SEAL PERFORMANCE NOT KNOWN, HOWEVER, PARTICLES MAY HAVE CONTRIBUTED TO DEGRADED CONDITION OF SEAL. 8. SEAL LEAKAGE REPORTED ON TABLE III WAS WITH PRESSURE APPLIED TO -37 CYLINDER HEAD AND LEAKAGE MEASURED AT -39 CYLINDER HEAD. LEAKAGE WAS NOT CHECKED IN REVERSE DIRECTION. 	5
ROD	12	507-1.250G	BAL-SEAL	<ol style="list-style-type: none"> 1. SEAL IN EXCELLENT CONDITION 2. ROD HAD NO WEAR OR SCORING; WEAR/POLISH AREA BARELY DISCERNIBLE. ROD SURFACE IN EXCELLENT CONDITION. 	6
ROD	6	7218FT-160-9009	GREENE, TWEED	<ol style="list-style-type: none"> 1. TEE SEAL SEVERELY WORN ON OUTER SEALING SURFACE; INNER SURFACE IN GOOD CONDITION. 2. OUTER TFE BACKUP SEVERELY WORN; INNER BACKUP IN GOOD CONDITION EXCEPT FOR SOME EDGE FEATHERING. 3. OUTER METAL BACKUP MISSING; SEVERAL SMALL PIECES FOUND IN RETURN CAVITIES; INNER BACKUP IN GOOD CONDITION. 4. ROD SURFACE HAD MINOR WEAR LINES; WEAR AREA MOSTLY POLISHED, NOT WORN. 5. SIGNIFICANT NUMBER OF LARGE BeCu PARTICLES FOUND INSIDE CYLINDER CHAMBER. BeCu PISTON STOP DID NOT CONTACT -39 CYLINDER HEAD AS DESIGNED. INSTEAD, O.D. EDGE OF STOP CONTACTED AN EDGE INSIDE CYLINDER HEAD. FULL LOAD OF PISTON TAKEN BY THE TWO EDGES. O.D. EDGE ON PISTON STOP WAS THEREFORE FRAGMENTED DUE TO INSUFFICIENT BEARING AREA. 6. TOTAL EFFECT OF BeCu PARTICLES ON ROD SEAL PERFORMANCE NOT KNOWN, HOWEVER PARTICLES MAY HAVE CONTRIBUTED TO DEGRADED CONDITION OF SEAL. 	7

LOCATION CODE

1, 2, etc. Seal in seal test fixture. See Figure 3.

A Seal in LHS actuator. See Figure 1.

TABLE IV (CONTINUED)

SEAL TYPE	LOCATION	PART NO.	DESIGNER/ SUPPLIER	COMMENTS	SEE FIGURE NO.
BOO	1	813122-218-14 NAS 1593-218	ROCKWELL/ SHAWHAN	1. O-RING SEVERELY WORN ON AREA FROM I.D. TO 120° OUTWARD; PRESSURE SIDE IN GOOD CONDITION. 2. OUTSIDE BACKUP WORN 0.010 IN. ON I.D.; I.D. FEATHERED MODERATELY. 3. INSIDE BACKUP IN EXCELLENT CONDITION. 4. BOO SURFACE HAD MINOR WEAR LINES; POLISHED AREAS WELL DEFINED; SURFACE IN EXCELLENT CONDITION.	8
BOO	7	820845-218 NAS 1593-218	SHAWHAN	1. O-RING HAD CONSIDERABLE EXTRUSION PINCHING AROUND CIRCUMFERENCE 2. OUTER POLYESTER BACKUP CRACKED MIDWAY BETWEEN I.D. AND O.D. AROUND NEARLY 360° OF CIRCUMFERENCE. CAUSE OF CRACK DUE TO 45° X .030 CHAMFER INADVERTENTLY PUT ON EDGE OF SEAL CAVITY; EDGE SHOULD HAVE HAD .003 -.010 RADIUS. I.D. OF BACKUP THEREFORE HAD NO SUPPORT. THIS CONDITION UNDOUBTEDLY CONTRIBUTED TO CRACK IN BACKUP RING AND O-RING PINCHING. 3. INNER POLYESTER BACKUP IN EXCELLENT CONDITION. 4. CAP SEAL WEARING SURFACE IN EXCELLENT CONDITION. 5. BUFFER RING IN EXCELLENT CONDITION. 6. BOO SURFACE HAD MINOR WEAR LINES; POLISHED AREAS WELL DEFINED; NO SIGNIFICANT WEAR.	9
DIAMETRAL	10	505-233G	BAL-SEAL	1. SEAL IN EXCELLENT CONDITION; NO EVIDENCE OF WEAR OR EXTRUSION.	10
DIAMETRAL	9	NAS 1593-233 MS 27595-233	ROCKWELL	1. O-RING AND TFE BACKUPS IN EXCELLENT CONDITION; NO EVIDENCE OF WEAR OR EXTRUSION.	10
DIAMETRAL	3	S31120-4	SHAWHAN	1. SEAL IN EXCELLENT CONDITION; NO EVIDENCE OF WEAR OR EXTRUSION.	10
DIAMETRAL	4	U-2410-03125-SED	UNITED AIRCRAFT	1. SEAL FAILED. METAL RING CRACKED AROUND 90° OF PERIPHERY.	10
DIAMETRAL	A	NAS 1593-116 MS 28774-116	ROCKWELL	(VALVE SLEEVE HAS 4 IDENTICAL DIAMETRAL SEALS; O-RING, ONE BACKUP) 1. ALL 4 O-RINGS IN EXCELLENT CONDITION. 2. ALL 4 TFE BACKUPS IN EXCELLENT CONDITION EXCEPT FOR MINOR FEATHERING ON OUTER EDGES.	2
FACE	8	5484-32900-160-0220	GREENE, TWEED	1. SEAL AND BACKUP IN EXCELLENT CONDITION; NO EVIDENCE OF WEAR OR EXTRUSION.	11
FACE	2	644A9X-0034-1	PRESSURE SCIENCE	1. SEAL IN EXCELLENT CONDITION EXCEPT FOR .006 IN. SET IN LIPS.	11
FACE	11	4252-03-25 NAS 1593-227	ROCKWELL	1. O-RING AND BACKUP IN EXCELLENT CONDITION.	11
FACE	5	U2410-02375-SED	UNITED AIRCRAFT	1. SEAL APPEARS TO BE IN EXCELLENT CONDITION; CANNOT REMOVE SEAL FROM GROOVE WITHOUT DAMAGING IT.	11
BOSS	17	NAS 1596-06	ROCKWELL	1. O-RING IN GOOD CONDITION EXCEPT FOR EXTRUSION AROUND PERIPHERY.	12
BOSS	A	831121-6	SHAWHAN	1. SEAL IN EXCELLENT CONDITION	12
BOSS	15	U-700413-063	UNITED AIRCRAFT	1. METAL O-RING HAS DISTORTIONS ON I.D. AND O.D.; SEAL CAVITY SMOOTH. CAUSE OF DISTORTIONS NOT APPARENT.	12
BOSS	16	U-700413-062	UNITED AIRCRAFT	1. METAL O-RING HAS DISTORTIONS ON I.D. AND O.D.; SEAL CAVITY SMOOTH. CAUSE OF DISTORTIONS NOT APPARENT. 2. TFE COATING PEELING OFF.	12

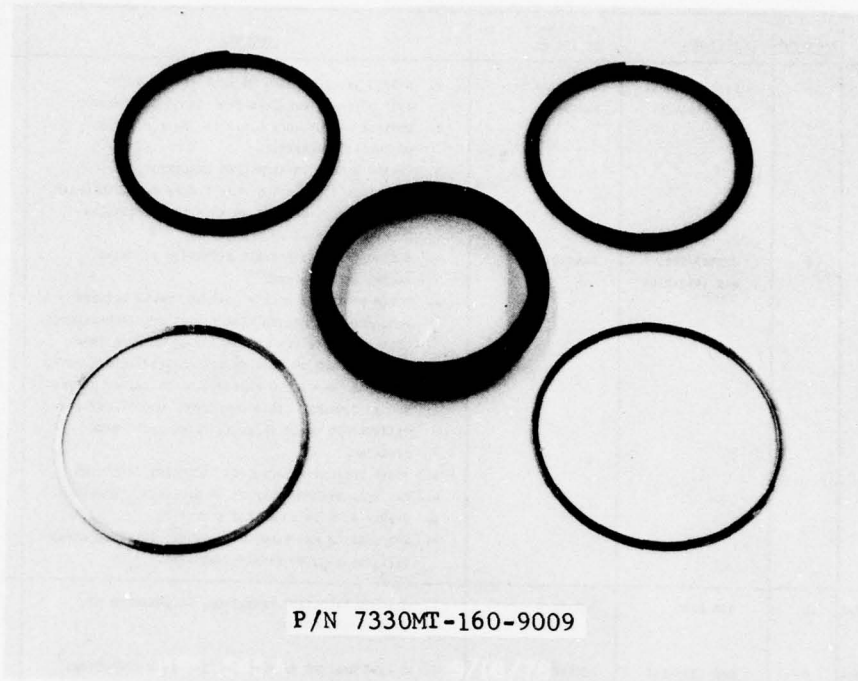


FIGURE 4 GREENE, TWEED PISTON SEAL

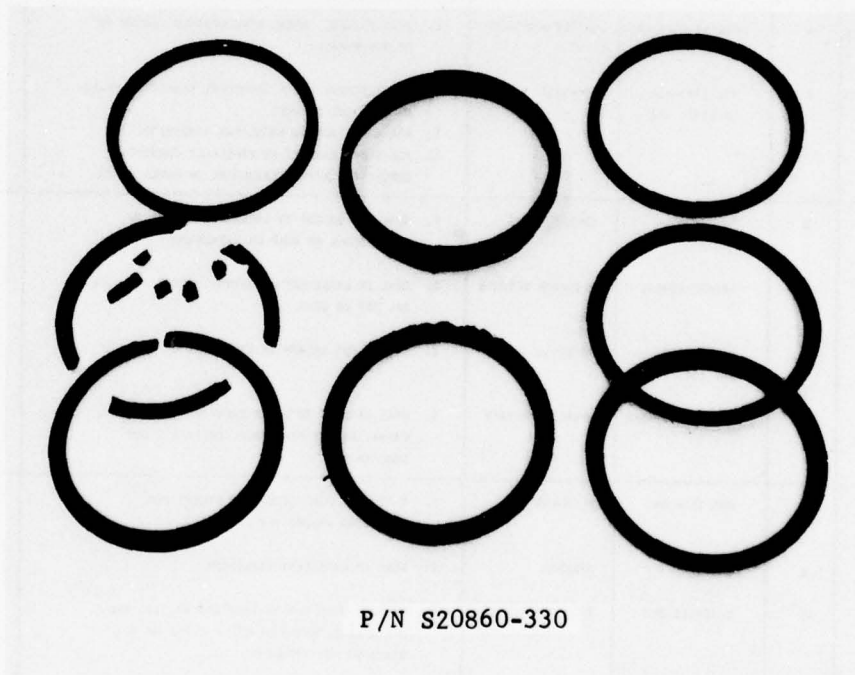


FIGURE 5 SHAMBAN PISTON SEAL

NADC-77218-30



P/N 507-1.250G

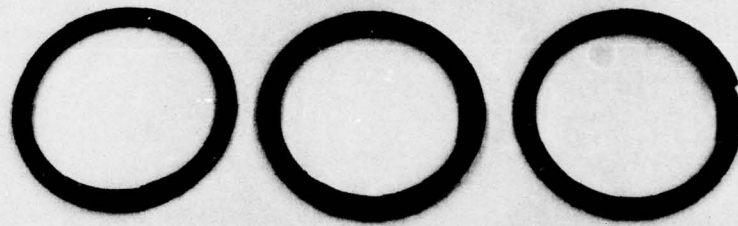
FIGURE 6 BAL-SEAL ROD SEAL



P/N 7218FT-160-9009

FIGURE 7 GREENE, TWEED ROD SEAL

P/N NAS 1593-218

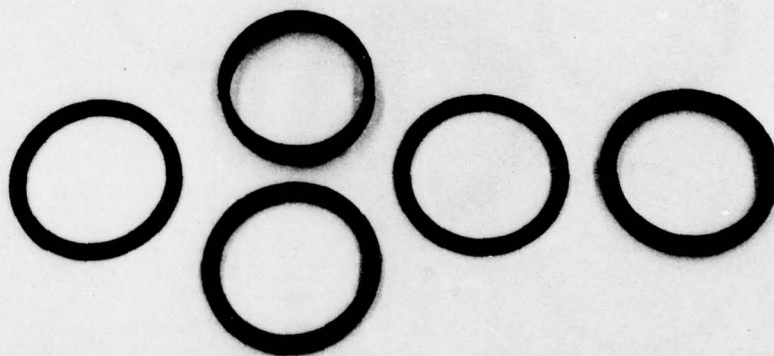


P/N S13122-218-14

H95-543E

9/18/78

FIGURE 8 ROCKWELL/SHAMBAN ROD SEAL



P/N S20865-218

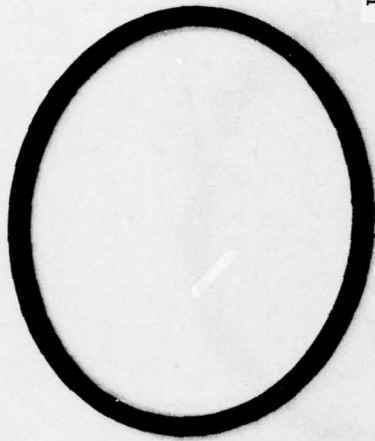
H95-543F

9/18/78

FIGURE 9 SHAMBAN ROD SEAL

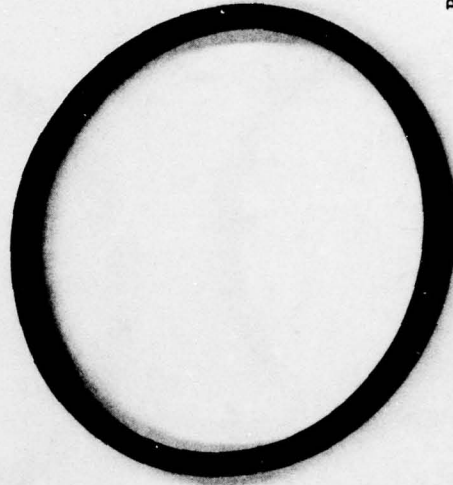
UNITED AIRCRAFT

P/N U-2410-03125-SED



BAL-SEAL

P/N 505-233G



SHAMBAN

P/N S31120-4



ROCKWELL

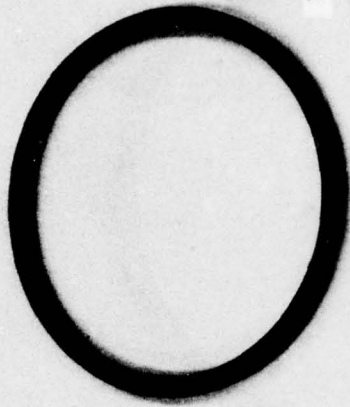
P/N NAS 1593-233



FIGURE 10 DIAMETRAL SEALS

UNITED AIRCRAFT

P/N U-2410-02375-SED



PRESSURE SCIENCE

P/N 664A9X-0034-1



ROCKWELL

P/N NAS 1593-227



GREENE, TWEED

P/N 5484-32900-160-0220

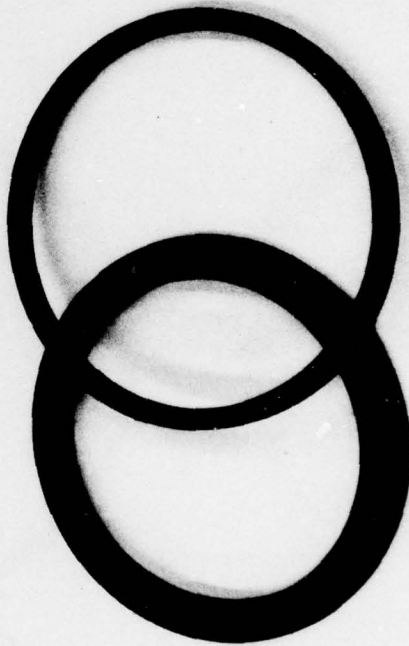


FIGURE 11 FACE SEALS

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A95-545 H

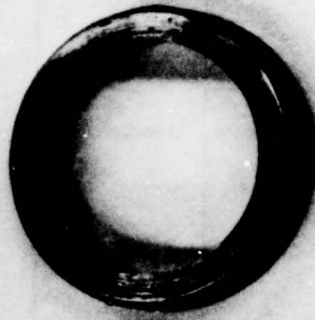
UNITED AIRCRAFT
P/N U-700413-062



UNITED AIRCRAFT
P/N U-700413-063



SHANBAN
P/N S31121-6



PARKER
P/N NAS 1596-06

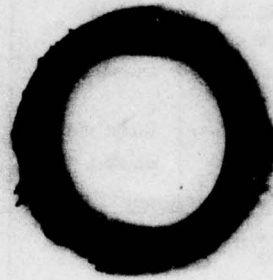


FIGURE 12 BOSS SEALS
9/18/78
H95-545J

TABLE V SEAL TEST SUMMARY

SEAL TYPE	LOCATION	PART NO.	DESIGNER/ SUPPLIER	SATISFACTORY	COMMENTS
PISTON	A	123DX-2040	COOK AIRTOMIC	NO	1. EXCESSIVE LEAKAGE AT 200 HOURS
PISTON	14	7330MT-160-9009	GREENE, TWEED	YES	1. EXCELLENT WEAR RESISTANCE 2. FITS STANDARD CAVITY
PISTON	13	S20860-330 NAS 1593-330	SHAMBAN	NO	1. BACKUP RING AND O-RING FAILED, HOWEVER CAUSE MAY HAVE BEEN DUE TO METALLIC PARTICLES GENERATED INSIDE SEAL TEST FIXTURE 2. SPECIAL CAVITIES REQUIRED 3. COMPLEX SEAL (8 PARTS) 4. BACKUP RINGS BRITTLE AND DIFFICULT TO INSTALL
ROD	A	SP-4246-4-162	COOK AIRTOMIC	YES	1. EXPENSIVE SEAL 2. NON-STANDARD CAVITY 3. HIGH FRICTION
ROD	12	507-1.250G	BAL-SEAL	YES	1. EXCELLENT WEAR RESISTANCE 2. SPLIT CAVITY REQUIRED 3. LIGHTER DUTY SEAL SHOULD BE EVALUATED
ROD	6	7218FT-160-9009	GREENE, TWEED	?	1. SEAL ON VERGE OF FAILURE AT 200 HOURS, CAUSE OF DETERIORATION MAY HAVE BEEN DUE TO METALLIC PARTICLES GENERATED INSIDE TEST FIXTURE 2. FITS STANDARD CAVITY 3. FURTHER TESTING REQUIRED FOR POSITIVE DETERMINATION
ROD	7	S20865-218 NAS 1593-218	SHAMBAN	YES	1. SEAL FUNCTIONED WELL IN SPITE OF DISCREPANCY IN CAVITY SHAPE 2. SPLIT CAVITY REQUIRED BECAUSE OF BRITTLE BACKUP RINGS
ROD	1	S13122-218-14 NAS 1593-218	ROCKWELL/ SHAMBAN	NO	1. O-RING WORN OUT AT 200 HOURS
DIAMETRAL	10	505-233G	BAL-SEAL	YES	1. EXCELLENT WEAR RESISTANCE
DIAMETRAL	9	NAS 1593-233 MS 27595-233	ROCKWELL	YES	2. STANDARD SEAL ELEMENTS IN MODIFIED STANDARD CAVITY
DIAMETRAL	3	S31120-4	SHAMBAN	YES	1. EXPENSIVE SEAL 2. NON-STANDARD CAVITY REQUIRED
DIAMETRAL	4	U-2410-03125-SED	UNITED AIRCRAFT	NO	1. SEAL FAILED (CRACK DEVELOPED)
DIAMETRAL	A	NAS 1593-116 MS 28774-116	ROCKWELL	YES	1. STANDARD SEAL ELEMENTS IN MODIFIED STANDARD CAVITY
FACE	8	5484-32900- 160-0220	GREENE, TWEED	YES	1. EXCELLENT WEAR RESISTANCE
FACE	2	664A9X-0034-1	PRESSURE SCIENCE	NO	1. EXCESSIVE LEAKAGE AT 200 HOURS
FACE	11	4252-03-25 NAS 1593-227	ROCKWELL	YES	1. STANDARD O-RING, SPECIAL SHAPED TFE BACKUP RING
FACE	5	U2410-02375-SED	UNITED AIRCRAFT	YES	1. HIGH PRELOAD REQUIRED
BOSS	17	NAS 1596-06	ROCKWELL	YES	1. STANDARD CONFIGURATION
BOSS	A	S31121-6	SHAMBAN	YES	1. EXPENSIVE SEAL 2. NON-STANDARD CAVITY REQUIRED
BOSS	15	U-700413-063	UNITED AIRCRAFT	NO	1. EXCESSIVE LEAKAGE
BOSS	16	U-700413-062	UNITED AIRCRAFT	NO	1. EXCESSIVE LEAKAGE
BOSS	18	NAS 1593-012 (RF9906-13)	ROSAN	YES	1. STANDARD ROSAN CONFIGURATION

LOCATION CODE

1, 2, etc. Seal in seal test fixture. See Figure 3.

A Seal in LMS actuator. See Figure 1. 30

During the first 100 hours of testing, Reference 7, a black residue was observed on filter elements in the system. Particles making up the residue were extremely small--less than one micron in size. The source and composition of the residue was not determined. Subsequently, information was obtained (Reference 12) which indicated the residue might be the result of fluid degradation caused by (1) oxidation, (2) thermal cracking, or (3) nitration, any of which could lead to the formation of insoluble deposits.

The reservoir was pressurized with nitrogen at 30 psig during the first 100 hours of endurance cycling. The second 100 hours of cycling were conducted with the reservoir pressurized by an inert gas--argon. This was done to minimize the possibility of oxidation/nitration reactions in the fluid.

High particle counts were observed in the 10-25 micron range based on fluid contamination checks made during the first 100 hours of cycling. All four filters in the system were rated for 10 microns (nominal). One filter element was changed for the second 100 hours of testing. The pump case drain element was replaced with a 5 micron absolute filter to lower the particle count in the 10-25 micron range. The three 10 micron (nominal) filter elements were cleaned ultrasonically prior to beginning the extended endurance test.

It should be noted that automatic particle counting equipment employed during the first 100 hours of testing was not capable of sensing contamination below 10-25 microns in size. The equipment has since been upgraded and currently counts particles in the 5 to 15 micron range.

Fluid viscosity and contamination were the parameters used to evaluate fluid performance. A decrease in viscosity would indicate poor shear stability; high particle counts in the 25 to 100 micron range would be evidence of poor lubricity and component wear. Viscosity and contamination of fluid samples taken during the test are listed below:

<u>Endurance Hours Completed</u>	<u>Fluid Viscosity, Centistokes</u>	<u>Fluid Contamination Number of Particles per 100 ml Micron Size Range</u>			
		<u>10-25</u>	<u>25-50</u>	<u>50-100</u>	<u>100+</u>
*0	17.48	6,665	0	0	0
*50	17.70	11,985	10	0	0
*100	17.71	49,265	20	0	0

*Data from Reference 7

		<u>Micron Size Range</u>				
		<u>5-15</u>	<u>15-25</u>	<u>25-50</u>	<u>50-100</u>	<u>100+</u>
100	16.85	95145	462	139	15	60
150	--	39318	315	18	1	0
200	16.88	3637	37	10	8	1
Class 5 System		87000	21400	3130	430	41
Class 1 System		4600	1340	210	28	3

System filter elements were visually examined at the 150 hour check point. There was no evidence of black residue on any of the four elements. The bowl on the pump case drain filter was remarkably clean. Small, visible wear particles which typically accumulate in case drain bowls were virtually absent.

The pressure drop across the pump case drain filter element began to increase noticeably at 60 hours and at 100 hours (end of the 200 hour test) reached approximately 60 psi during pump cut-off. The Δp was 10 psi at the start of the extended endurance test. The 5 micron element thus appeared to be loading up; this was anticipated.

The four filters in the system were visually examined at the conclusion of testing. All the elements contained a black residue, however the accumulation was not as heavy as that reported in Reference 7. Normal quantities of visible wear particles were observed in each of the filter bowls.

2.9 TUBING, FITTINGS, AND HOSES

The following components were evaluated:

<u>Description, Size</u>	<u>Part Number</u>	<u>Manufacturer</u>
Tubing, 3/16 x .020 1/4 x .025 3/8 x .038	21-6-9 CRES	Trent Tube Division of Colt Industries
Fitting, -3, -4, -6	R44101 R44272 R44273	Resistoflex Corporation
Fitting, -6	RF9906-13	Rosán, Incorporated
Hose, -4 x 20 in.	37000004	Titeflex Division of Atlas Corporation
Hose, -6 x 20 in.	R44598-0200	Resistoflex Corporation

The tubing, fittings, and hoses were subjected to a total of 1,760,000 pressure pulsations in the range of 8000 ⁺⁵⁰⁰₋₂₀₀₀ psig. Performance of all components was satisfactory.

3.0 DISCUSSION

The most critical components in an aircraft hydraulic system are pumps and seals--failure of either can result in serious circumstances. Testing conducted in the LHS program has demonstrated that current state-of-the-art hardware designed for use at 8000 psi performs well.

Pump performance in the extended endurance test was completely satisfactory. There were no malfunctions, discrepancies, or trends indicating possible problems. Pump wear was normal. Future LHS pumps will be new and original designs rather than modified existing designs, References 3 and 8. This will result in a more optimized unit.

Seal performance in the 200 hour endurance test was better than expected. Standard O-rings and TFE backups were found to be satisfactory for use in static applications (diametral, face, and boss type seals). This was a major determination that will minimize costs and greatly simplify conversion from 3000 to 8000 psi systems. Off-the-shelf components performed well in dynamic seal applications. This, again, was an important finding since special piston and rod seals will not have to be developed for 8000 psi actuators.

A black residue was observed on the filter elements at the conclusion of testing; the residue was also noted during the first 100 hours of cycling, Reference 7. The tiny black particles (<1 micron in size) were suspected of being caused by fluid oxidation, thermal cracking, or nitration, Reference 12. In an attempt to impede formation of the particles, the system reservoir was pressurized with argon during the extended endurance test. (Nitrogen was used for the first 100 hours of testing, Reference 7.) Argon did not eliminate the residue, but did appear to reduce the quantity of particles developed.

A sample of the black residue was examined by the Rockwell International Science Center in Thousand Oaks, California. An Electron Spectroscopy for Chemical Analysis (ESCA) was employed to determine constituents in the residue. The results were:

Carbon (as graphite)	95%
Carbon bonded to oxygen (CO)	4%
Sulphur	less than 0.1% *
Silicon	less than 0.1% *
Iron	less than 0.1% *
Nitrogen	less than 0.1% *
Fluorocarbons	less than 0.1% *

* Amount below instrument sensitivity

Although not positively established, the graphite particles may be the result of a breakdown in the hydraulic fluid hydrocarbon molecules. Effects of this on component/system performance were as follows:

Deterioration of fluid properties (viscosity and lubricity)	None
Fluid erosion on orifices and rubbing surfaces (due to microscopic graphite particles)	None
Loss of hydraulic fluid (due to molecular breakdown)	Not discernible
Fluid filtration	May be affected

4.0 RECOMMENDATIONS

Results of the 200 hour seal endurance test were encouraging. Of the 22 different seals evaluated, 14 (+1 undecided) were satisfactory. Factors other than wear resistance and sealing capability must be considered, however, in selecting seals for aircraft applications. These factors include envelope, simplicity, ease of assembly, cavity requirements, shelf life, friction, cost, and others. Based on the endurance test results and important secondary considerations, it is recommended that additional testing be conducted on seals similar to those listed below. These tests should be performed as an integral part of the LHS Advanced Development Program, Reference 10.

<u>Seal Type</u>	<u>Part No.</u>
Piston	Greene, Tweed P/N 7330MT-160-9009
Rod	Bal-Seal P/N 507-1.250 G
Rod	Shamban P/N S20865-218
Rod	Greene, Tweed P/N 7218FT-160-9009
Diametral	Standard MS elements
Face	Standard MS elements
Boss	Standard MS elements

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LIST OF ABBREVIATIONS

AFCAS	Advanced Flight Control Actuation System
approx.	approximately
avg	average
Be	beryllium
BTU/min	British Thermal Units per minute
CAD	Columbus Aircraft Division
cc/min	cubic centimeters per minute
CIPR	cubic inches per revolution
CRES	corrosion resistant
Cu	copper
displ.	displacement
ea.	each
est.	estimated
gpm	gallons per minute
I.D.	inside diameter
in.	inch
lb-in	pound-inch (torque)
LHS	Lightweight Hydraulic System
max.	maximum
ml	milliliter
M/N	model number

LIST OF ABBREVIATIONS - (CONT'D.)

NADC	Naval Air Development Center
No.	number
O.D.	outside diameter
ΔP	differential pressure
P/N	part number
psi	pounds per square inch
psig	pounds per square inch gage pressure
rpm	revolutions per minute
S/N	serial number
Sn	tin
TFE	tetrafluoroethylene
μ	micron